

# FCNC Processes Waiting for the Next Decade \*

ANDRZEJ J. BURAS

Technical University Munich, Physics Department, D-85748 Garching, Germany,  
TUM Institute for Advanced Study, D-80333 München, Germany

FCNC processes are expected to offer us a deep insight into the physics at very short distance scales. We present a list of 20 goals in quark and lepton flavour physics that could be reached already in the next decade. This list includes also flavour conserving observables like electric dipole moments of the neutron and leptons and  $(g - 2)_\mu$ . Subsequently we will present some aspects of these goals by concentrating on supersymmetric flavour models. A much more extensive presentation of this material can be found in my recent EPS09 talk [1].

PACS numbers: 11.10.Kk, 12.15.Ji, 12.60.-i, 13.20.Eb, 13.20.He

## 1. Overture

Flavour-violating and CP-violating processes are very strongly suppressed and are governed by quantum fluctuations that allow us to probe energy scales far beyond the ones explored by the LHC and future colliders. Indeed energy scales as high as 200 TeV corresponding to short distances in the ballpark of  $10^{-21}$  m and even shorter distance scales can be probed, albeit indirectly, in this manner. Consequently frontiers in probing ultrashort distance scales belong to flavour physics or more concretely to very rare processes like particle-antiparticle mixing, rare decays of mesons and of the top quark, CP violation and lepton flavour violation. Also electric dipole moments and  $(g - 2)_\mu$  belong to these frontiers even if they are flavour conserving. While such tests are not limited by the available energy, they are limited by the available precision. The latter has to be very high as the Standard Model (SM) has been until now very successful and finding departures from its predictions has become a real challenge.

Personally I expect that the coming decade will become the decade of discoveries not only at the LHC but in particular in high precision flavour

---

\* Presented at the Flavianet topical workshop *Low energy constraints on extensions of the Standard Model*

experiments like the LHCb, Super-Belle, Super Flavour Facility (SFF) in Frascati and dedicated rare  $K$  experiments around the world. Also flavour conserving observables like electric dipole moments of the neutron and leptons and  $(g - 2)_\mu$  will play an important role in this progress.

Recently, I have given a talk at EPS09 in Cracow summarizing the present status of flavour theory and presenting flavour expectations for the coming decade [1]. In view of space limitations I can discuss here only few points made already in my EPS09 talk where further details can be found. In particular very few references will be given here. This is, I hope, compensated by roughly 300 references given in the EPS09 writeup.

This presentation consists of three parts. First I will make a list of twenty most important goals in this field for the coming decade. In the second part I will concentrate on a few topics that I find particularly important and interesting. The third part is dominated by a number of enthusiastic statements that close this report.

## 2. Twenty Goals in Flavour Physics for the Next Decade

We will now list twenty goals in Flavour Physics for the coming decade. The order in which these goals will be listed does not represent by any means a ranking in importance.

### Goal 1: The CKM Matrix from Tree Level Decays

This determination would give us the values of the elements of the CKM matrix without new physics (NP) pollution. From the present perspective most important are the determinations of  $|V_{ub}|$  and  $\gamma$  because they are presently not as well known as  $|V_{cb}|$  and  $|V_{us}|$ . However, a precise determination of  $|V_{cb}|$  is also important as  $\varepsilon_K$ ,  $Br(K^+ \rightarrow \pi^+ \nu \bar{\nu})$  and  $Br(K_L \rightarrow \pi^0 \nu \bar{\nu})$  are roughly proportional to  $|V_{cb}|^4$ . While Super-B facilities accompanied by improved theory should be able to determine  $|V_{ub}|$  and  $|V_{cb}|$  with precision of 1 – 2%, the best determination of the angle  $\gamma$  in the first half of the next decade will come from the LHCb. An error of a few degrees on  $\gamma$  should be achievable around 2015 and this measurement could be further improved at Super-B machines.

### Goal 2: Improved Lattice Calculations of Hadronic Parameters

The knowledge of meson decay constants  $F_{B_s}$ ,  $F_{B_d}$  and of various  $B_i$  parameters with high precision would allow in conjunction with Goal 1 to make precise calculations of the  $B_{s,d}$  mixing mass differences  $\Delta M_{s,d}$ ,  $\varepsilon_K$ ,  $Br(B_{s,d} \rightarrow \mu^+ \mu^-)$  and of other observables in the SM. We could then directly see whether the SM is capable in describing these observables or not. The most recent unquenched calculations allow for optimism and in fact a very significant progress in the calculation of  $\hat{B}_K$ , relevant for  $\varepsilon_K$ , has been made recently. We will discuss its implications in Section 3.

**Goal 3: Is  $\varepsilon_K$  consistent with  $S_{\psi K_S}$  within the SM?**

The recent improved value of  $\hat{B}_K$  from unquenched lattice QCD accompanied by a more careful look at  $\varepsilon_K$  [2] suggests that the size of CP violation measured in  $B_d \rightarrow \psi K_S$ , might be insufficient to describe  $\varepsilon_K$  within the SM. Clarification of this new tension is important as the  $\sin 2\beta - \varepsilon_K$  correlation in the SM is presently the only relation between CP violation in  $B_d$  and  $K$  systems that can be tested experimentally. We will return to this issue in Section 3.

**Goal 4: Is  $S_{\psi\phi}$  much larger than its tiny SM value?**

Within the SM CP violation in the  $B_s$  system is predicted to be very small. The best known representation of this fact is the value of the mixing induced CP asymmetry:  $(S_{\psi\phi})_{\text{SM}} \approx 0.04$ . The present data from CDF and D0 indicate that CP violation in the  $B_s$  system could be much larger  $S_{\psi\phi} = 0.81^{+0.12}_{-0.32}$ . This is a very interesting deviation from the SM. Its clarification is of utmost importance and I will return to this question in Section 3. Fortunately, we should know the answer to this question within the coming years as CDF, D0, LHCb, ATLAS and CMS will make big efforts to measure  $S_{\psi\phi}$  precisely.

**Goal 5: Non-Leptonic Two Body B Decays**

The best information on CP violation in the  $B$  system to date comes from two body non-leptonic decays of  $B_d$  and  $B^\pm$  mesons. The LHCb will extend these studies in an important manner to  $B_s$  and  $B_c$  decays. This is clearly a challenging field not only for experimentalist but in particular for theorists due to potential hadronic uncertainties. Yet, in the last ten years an impressive progress has been made in measuring many channels, in particular  $B \rightarrow \pi\pi$  and  $B \rightarrow \pi K$  decays, and developing a number of methods to analyze these data.

I think this field will continue to be important for the tests of the CKM framework in view of very many channels whose branching ratios should be measured in the next decade with a high precision. On the other hand in view of potential hadronic uncertainties present in the branching ratios and direct CP asymmetries these observables in my opinion will not provide definite answers about NP if the latter contributes to them only at the level of 20% or less. On the other hand mixing induced CP-asymmetries like  $S_{\psi K_S}$ ,  $S_{\psi\phi}$  and alike being theoretically much cleaner will continue to be very important for the tests of NP.

**Goal 6:  $Br(B_{s,d} \rightarrow \mu^+\mu^-)$**

In the SM and in several of its extensions  $Br(B_s \rightarrow \mu^+\mu^-)$  is found in the ballpark of  $3 - 5 \cdot 10^{-9}$ , which is by an order of magnitude lower than the present bounds from CDF and D0. A discovery of  $Br(B_{s,d} \rightarrow \mu^+\mu^-)$  at  $\mathcal{O}(10^{-8})$  would be a clear signal of NP, possibly related to Higgs penguins. The LHCb can reach the SM level for this branching ratio in the first years of

its operation. From my point of view, similar to  $S_{\psi\phi}$ , precise measurements of  $Br(B_s \rightarrow \mu^+\mu^-)$  and  $Br(B_d \rightarrow \mu^+\mu^-)$  are among the most important goals in flavour physics in the coming years. We will discuss both decays in Section 3.

**Goal 7:  $B \rightarrow X_{s,d}\gamma$ ,  $B \rightarrow K^*(\varrho)\gamma$  and  $A_{\text{CP}}^{\text{dir}}(b \rightarrow s\gamma)$**

The radiative decays in question, in particular  $B \rightarrow X_s\gamma$ , played an important role in constraining NP in the last 15 years because both the experimental data and also the theory have been already in a good shape for some time with the NNLO calculations of  $Br(B \rightarrow X_s\gamma)$  being at the forefront of perturbative QCD calculations in weak decays. Both theory and experiment reached roughly 10% precision and the agreement of the SM with the data is good implying not much room left for NP contributions. Still further progress both in theory and experiment should be made to further constrain NP models. Of particular interest is the direct CP asymmetry  $A_{\text{CP}}^{\text{dir}}(b \rightarrow s\gamma)$  that is similar to  $S_{\psi\phi}$  predicted to be tiny (0.5%) in the SM but could be much larger in some of its extensions.

**Goal 8:  $B \rightarrow X_sl^+l^-$  and  $B \rightarrow K^*l^+l^-$**

While the branching ratios for  $B \rightarrow X_sl^+l^-$  and  $B \rightarrow K^*l^+l^-$  put already significant constraints on NP, the angular observables, CP-conserving ones like the well known forward-backward asymmetry and CP-violating ones will definitely be very useful for distinguishing various extensions of the SM. Recently, a number of detailed analyses of various CP averaged symmetries and CP asymmetries provided by the angular distributions in the exclusive decay  $B \rightarrow K^*(\rightarrow K\pi)l^+l^-$  have been performed. In particular the zeroes of some of these observables can be accurately predicted. Belle and BaBar provided already interesting results for the best known forward-backward asymmetry but the data have to be improved in order to see whether some sign of NP is seen in this asymmetry. Future studies by the LHCb and Super-B machines will be able to contribute here in a significant manner.

**Goal 9:  $B^+ \rightarrow \tau^+\nu$  and  $B^+ \rightarrow D^0\tau^+\nu$**

The SM expression for the branching ratio of the tree-level decay  $B^+ \rightarrow \tau^+\nu$  is subject to parametric uncertainties induced by  $F_{B^+}$  and  $V_{ub}$ . In order to find the SM prediction for this branching ratio we can express them in terms of  $\Delta M_{s,d}$  and  $S_{\psi K_S}$ , all to be taken from experiment. We then find [3]

$$Br(B^+ \rightarrow \tau^+\nu)_{\text{SM}} = (0.80 \pm 0.12) \times 10^{-4}. \quad (1)$$

This result agrees well with a recent result presented by the UTfit collaboration [4].

On the other hand, the present experimental world average based on results by BaBar and Belle reads

$$Br(B^+ \rightarrow \tau^+\nu)_{\text{exp}} = (1.73 \pm 0.35) \times 10^{-4}, \quad (2)$$

and is roughly by a factor of 2 higher than the SM value. We can talk about a tension at the  $2.5\sigma$  level. Interestingly, the tension between theory and experiment in the case of  $Br(B^+ \rightarrow \tau^+\nu)$  increases in the presence of a tree level  $H^\pm$  exchange which interferes destructively with the  $W^\pm$  contribution.

The full clarification of a possible discrepancy between the SM and the data will have to wait for the data from Super-B machines. Also improved values for  $F_B$  from lattice and  $|V_{ub}|$  from tree level decays will be important if some NP like charged Higgs is at work here. The decay  $B^+ \rightarrow D^0\tau^+\nu$  being sensitive to different couplings of  $H^\pm$  can contribute significantly to this discussion but formfactor uncertainties make this decay less theoretically clean.

#### Goal 10: Rare Kaon Decays

Among the top highlights of flavour physics in the next decade will be the measurements of the branching ratios of two *golden modes*  $K^+ \rightarrow \pi^+\nu\bar{\nu}$  and  $K_L \rightarrow \pi^0\nu\bar{\nu}$ .  $K^+ \rightarrow \pi^+\nu\bar{\nu}$  is CP conserving while  $K_L \rightarrow \pi^0\nu\bar{\nu}$  is governed by CP violation. Both decays are dominated in the SM and many of its extensions by  $Z$  penguin contributions. It is well known that these decays are theoretically very clean and are known in the SM including NNLO QCD corrections and electroweak corrections. Moreover, extensive calculations of isospin breaking effects and non-perturbative effects have been done. The present theoretical uncertainties in  $Br(K^+ \rightarrow \pi^+\nu\bar{\nu})$  and  $Br(K_L \rightarrow \pi^0\nu\bar{\nu})$  are at the level of  $2 - 3\%$  and  $1 - 2\%$ , respectively.

Let me stress that the measurements of the branching ratios in question with an accuracy of 10% will give us a very important insight into the physics at short distance scales. NA62 at CERN in the case of  $K^+ \rightarrow \pi^+\nu\bar{\nu}$  and KOTO at J-PARC in the case of  $K_L \rightarrow \pi^0\nu\bar{\nu}$  will tell us how these two decays are affected by NP.

The decays  $K_L \rightarrow \pi^0 l^+ l^-$  are not as theoretically clean as the  $K \rightarrow \pi\nu\bar{\nu}$  channels and are less sensitive to NP contributions but they probe different operators beyond the SM and having accurate branching ratios for them would certainly be very useful.

#### Goal 11: $B \rightarrow X_s\nu\bar{\nu}$ , $B \rightarrow K^*\nu\bar{\nu}$ and $B \rightarrow K\nu\bar{\nu}$

Also  $B$  decays with  $\nu\bar{\nu}$  in the final state provide a very good test of modified  $Z$  penguin contributions, but their measurements appear to be even harder than those of the rare K decays just discussed.

The inclusive decay  $B \rightarrow X_s\nu\bar{\nu}$  is theoretically as clean as  $K \rightarrow \pi\nu\bar{\nu}$  decays but the parametric uncertainties are a bit larger. The two exclusive channels are affected by formfactor uncertainties but recently in the case of  $B \rightarrow K^*\nu\bar{\nu}$  and  $B \rightarrow K\nu\bar{\nu}$  significant progress has been made. The interesting feature of these three  $b \rightarrow s\nu\bar{\nu}$  transitions, in particular when taken together, is their sensitivity to right-handed currents. Super-B machines should be able to measure them at a satisfactory level.

**Goal 12: Calculations of Hadronic Matrix Elements in  $\varepsilon'/\varepsilon$**

One of the important actors of the previous decade in flavour physics was the ratio  $\varepsilon'/\varepsilon$  that measures the size of the direct CP violation in  $K_L \rightarrow \pi\pi$  relative to the indirect CP violation described by  $\varepsilon_K$ . In the SM  $\varepsilon'$  is governed by QCD penguins but receives also an important destructively interfering contribution from electroweak penguins that is generally much more sensitive to NP than the QCD penguin contribution.

Here the problem is the strong cancellation of QCD penguin contributions and electroweak penguin contributions to  $\varepsilon'/\varepsilon$  and in order to obtain useful predictions the precision on the corresponding hadronic parameters  $B_6$  and  $B_8$  should be at least 10%. Lattice theorists hope to make progress on  $B_6$ ,  $B_8$  and other  $\varepsilon'/\varepsilon$  related hadronic matrix elements in the coming decade. This would really be good, as the calculations of short distance contributions to this ratio (Wilson coefficients of QCD and electroweak penguin operators) have been known already for 16 years at the NLO level and the experimental world average from NA48 and KTeV  $\varepsilon'/\varepsilon = (16.8 \pm 1.4) \cdot 10^{-4}$ , could have an important impact on several extensions of the SM discussed in the literature if  $B_6$  and  $B_8$  were known.

**Goal 13: CP Violation in Charm Decays and  $D^+(D_s^+) \rightarrow l^+\nu$**

Charm physics has been for many years shadowed by the successes of  $K$  decays and  $B$  decays, although a number of experimental groups and selected theorists have made a considerable effort to study them. This is due to the GIM mechanism being very effective in suppressing the FCNC transitions in this sector, long distance contributions plugging the evaluation of the  $\Delta M_D$  and insensitivity to top physics in the loops. However, large  $D^0 - \bar{D}^0$  mixing discovered in 2007 and good prospects for the study of CP violation in these decays at Super Belle and SFF in Frascati gave a new impetus to this field. Also leptonic decays of  $D$  mesons remain to be important.

**Goal 14: CP Violation in the Lepton Sector and  $\theta_{13}$**

The mixing angles  $\theta_{12}$  and  $\theta_{23}$  are already known with respectable precision. The obvious next targets in this field are  $\theta_{13}$  and the CP phase  $\delta_{\text{PMNS}}$ . Clearly the discovery of CP violation in the lepton sector would be a very important mile stone in particle physics for many reasons. In particular the most efficient explanations of the BAU these days follow from leptogenesis. While in the past the necessary size of CP violation was obtained from new sources of CP violation at very high see-saw scales, the inclusion of flavour effects, in particular in resonant leptogenesis, gave hopes for the explanation of the BAU using only the phases in the PMNS matrix. This implies certain conditions for the parameters of this matrix, that is the relevant  $\delta_{\text{PMNS}}$ , two Majorana phases and  $\theta_{13}$ .

**Goal 15: Tests of  $\mu - e$  and  $\mu - \tau$  Universalities**

Lepton flavour violation (LFV) and the related breakdown of universality can be tested in meson decays by studying the ratios

$$R_{\mu e} = \frac{Br(K^+ \rightarrow \mu^+ \nu)}{Br(K^+ \rightarrow e^+ \nu)}, \quad R_{\mu \tau} = \frac{Br(B^+ \rightarrow \mu^+ \nu)}{Br(B^+ \rightarrow \tau^+ \nu)}, \quad (3)$$

where the sum over different neutrino flavours is understood. The first case is a high precision affair both for experimentalists and theorists as both groups decreased the uncertainties in  $R_{\mu e}$  well below 1% with a precision of 0.5% recently achieved at CERN. It will continue to constitute an important test of the  $\mu - e$  universality. The ratio  $R_{\mu \tau}$  is even more sensitive to NP contributions but it will still take some time before it will be known with good precision.

**Goal: 16 Flavour Violation in Charged Lepton Decays (LFV)**

The search for LFV clearly belongs to the most important goals in flavour physics. In the SM with right-handed Dirac neutrinos, the smallness of neutrino masses implies tiny branching ratios for LFV processes. For instance  $Br(\mu \rightarrow e \gamma)_{\text{SM}} \approx 10^{-54}$ , which is more than 40 orders of magnitude below the 90% C.L. upper bound from the MEGA Collaboration

$$Br(\mu \rightarrow e \gamma) < 1.2 \cdot 10^{-11}. \quad (4)$$

Therefore any observation of LFV would be a clear sign of NP. While we hope that new flavoured leptons will be observed at the LHC, even if this will not turn out to be the case, LFV has the following virtue: sensitivity to short distance scales as high as  $10^{10} - 10^{14}$  GeV, in particular when the see-saw mechanism is at work.

In order to distinguish various NP scenarios that come close to the bound in (4) it will be essential to study a large set of decays to three leptons in the final state. There exist also interesting correlations between leptogenesis and LFV. Additional correlations relevant for LFV will be discussed in Section 3.

**Goal 17: Electric Dipole Moments**

So far CP violation has only been observed in flavour violating processes. Non-vanishing electric dipole moments (EDMs) signal CP violation in flavour conserving transitions. In the SM CP violation in flavour conserving processes is very strongly suppressed as best expressed by the SM values of electric dipole moments of the neutron and electron that amount to

$$d_n \approx 10^{-32} \text{ e cm.} \quad d_e \approx 10^{-38} \text{ e cm.} \quad (5)$$

This should be compared with the present experimental bounds

$$d_n \leq 2.9 \cdot 10^{-26} \text{ e cm.} \quad d_e \leq 1.6 \cdot 10^{-27} \text{ e cm.} \quad (6)$$



They should be improved in the coming years by 1-2 orders of magnitude.

Similarly to LFV, an observation of a non-vanishing EDM would imply necessarily NP at work. Consequently correlations between LFV and EDMs in specific NP scenarios are to be expected, in particular in supersymmetric models, as both types of observables are governed in SUSY by dipole operators. We will encounter some examples in Section 3.

**Goal 18: Clarification of the  $(g - 2)_\mu$  Anomaly**

The measured anomalous magnetic moment of the electron,  $(g - 2)_e$ , is in an excellent agreement with SM expectations. On the other hand, the measured anomalous magnetic moment of the muon,  $(g - 2)_\mu$ , is roughly by  $3\sigma$  larger than its SM value. Hadronic contributions to  $(g - 2)_\mu$  make the comparison of data and theory a bit problematic. Yet, as this anomaly has been with us already for a decade and tremendous effort by a number of theorists has been made to clarify this issue, this anomaly could indeed come from NP.

The MSSM with large  $\tan\beta$  and sleptons with masses below 400 GeV is capable of reproduce the experimental value of  $(g - 2)_\mu$  provided the  $\mu$  parameter in the Higgs Lagrangian has a specific sign. At SFF also  $(g - 2)_\tau$  can be measured and it is also sensitive to NP contributions.

**Goal 19: Flavour Violation at High Energy**

Our presentation deals mainly with tests of flavour and CP violation in low energy processes. However, at the LHC it will be possible to investigate these phenomena also in high energy processes, in particular in top quark decays.

**Goal 20: Construction of a New Standard Model (NSM)**

Finally, in view of so many parameters present in basically all extensions of the SM like the MSSM, the LHT model and RS models, it is unlikely from my point of view that any of the models studied presently in the literature will turn out to be the new model of elementary particle physics. On the other hand various structures, concepts and ideas explored these days in the context of specific models may well turn out to be included in the NSM that is predictive, consistent with all the data and giving explanation of observed hierarchies in fermion masses and mixing matrices. While these statements may appear to be very naive, it is a fact that the construction of the NSM is the main goal of elementary particle physics and every theorist, even as old as I am, has a dream that the future NSM will carry her (his) name.

### 3. Waiting for Signals of New Physics in FCNC Processes

#### 3.1. Strategies for the Search for New Physics in the Next Decade

Let us first emphasize that until now only  $\Delta F = 2$  FCNC processes could be used in the UTfits. The measured  $B \rightarrow X_s \gamma$  and  $B \rightarrow X_s l^+ l^-$  decays



and their exclusive counterparts are sensitive to  $|V_{ts}|$  that has nothing to do with the usual UT plots. The same applies to the observables in the  $B_s$  system, which with the  $S_{\psi\phi}$  anomaly observed by CDF and D0 and the studies of rare  $B_s$  decays at the Tevatron and later at the LHC are becoming central for flavour physics. Obviously these comments also apply to all lepton flavour violating processes.

In this context a special role is played by  $Br(K^+ \rightarrow \pi^+ \nu \bar{\nu})$  and  $Br(K_L \rightarrow \pi^0 \nu \bar{\nu})$  as their values allow a theoretically clean construction of the UT in a manner complementary to its present determinations: the height of the UT is determined from  $Br(K_L \rightarrow \pi^0 \nu \bar{\nu})$  and the side  $R_t$  from  $Br(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ . Thus projecting the results of future experimental results for these two branching ratios on the  $(\bar{\varrho}, \bar{\eta})$  plane could be a very good test of the SM.

Yet, generally I do not think that in the context of the search for the NSM (see Goal 20) it is a good strategy to project the results of all future measurements of rare decays on the  $(\bar{\varrho}, \bar{\eta})$  plane or any other of five planes related to the remaining unitarity triangles. This would only teach us about possible inconsistencies within the SM but would not point towards a particular NP model.

In view of this, here comes a proposal for the strategy for searching for NP in the next decade, in which hopefully the side  $R_b$  and the angle  $\gamma$  in the UT will be precisely measured, CP violation in the  $B_s$  system explored and many goals listed in the previous section reached. This strategy proceeds in three steps:

#### Step 1

In order to study transparently possible tensions between  $\varepsilon_K$ ,  $\sin 2\beta$ ,  $|V_{ub}|$ ,  $\gamma$  and  $R_t$  let us leave the  $(\bar{\varrho}, \bar{\eta})$  plane and go to the  $R_b - \gamma$  plane [5] suggested already several years ago and recently strongly supported by the analysis in [3, 6]. The  $R_b - \gamma$  plane is shown in Fig. 1. We will explain this figure in the next subsection.

#### Step 2

In order to search for NP in rare  $K$ ,  $B_d$ ,  $B_s$ ,  $D$  decays, in CP violation in  $B_s$  and charm decays, in LFV decays, in EDMs and  $(g - 2)_\mu$  let us go to specific plots that exhibit correlations between various observables. As we will see below such correlations will be crucial to distinguish various NP scenarios. Of particular importance are the correlations between the CP asymmetry  $S_{\psi\phi}$  and  $B_s \rightarrow \mu^+ \mu^-$ , between the anomalies in  $S_{\phi K_s}$  and  $S_{\psi\phi}$ , between  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  and  $K_L \rightarrow \pi^0 \nu \bar{\nu}$ , between  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  and  $S_{\psi\phi}$ , between  $S_{\phi K_s}$  and  $d_e$ , between  $S_{\psi\phi}$  and  $(g - 2)_\mu$  and also those involving lepton flavour violating decays.

#### Step 3

In order to monitor the progress made in the next decade when additional data on flavour changing processes will become available, it is useful

to construct a “DNA-Flavour Test” of NP models [3] including Supersymmetry, the LHT model, the RS models and various supersymmetric flavour models and other models, with the aim to distinguish between these NP scenarios in a global manner.

Having this strategy in mind we will in the rest of this writing illustrate Steps 1 and 2 on several examples. The full table representing “DNA-Flavour Test” can be found in [3]. Here we will reduce the illustration of Step 3 to few observables.

### 3.2. Tension in the $R_b - \gamma$ Plane

Recently, in connection with Goal 3 some tensions in the UTFits have been identified in [2, 7].

In order to see them transparently let us have now a look at the  $R_b - \gamma$  plane in Fig. 1 taken from [3]. There, in the upper left plot the *blue (green)* region corresponds to the  $1\sigma$  allowed range for  $\sin 2\beta$  ( $R_t$ ) as calculated in the SM. The *red* region corresponds to  $|\epsilon_K|$  in the SM. Finally the solid black line corresponds to  $\alpha = 90^\circ$  that is close to the value favoured by UT fits and other analyses.

It is evident that there is a tension between various regions as there are three different values of  $(R_b, \gamma)$ , depending on which two constraints are simultaneously applied. The four immediate solutions to this tension are as follows:

1. There is a positive NP effect in  $\epsilon_K$  while  $\sin 2\beta$  and  $\Delta M_d/\Delta M_s$  are SM-like [2], as shown by the upper right plot of Fig. 1. The required effect in  $\epsilon_K$  could be for instance achieved within models with CMFV by a positive shift in the relevant one-loop box diagram function. Alternatively, new non-minimal sources of flavour violation relevant only for the  $K$  system could solve the problem. Note that this solution corresponds to  $\gamma \simeq 66^\circ$ ,  $R_b \simeq 0.36$  and  $\alpha \simeq 93^\circ$  in accordance with the usual UT analysis.

2.  $\epsilon_K$  and  $\Delta M_d/\Delta M_s$  are NP free while  $S_{\psi K_S}$  is affected by a NP phase  $\phi_{B_d}$  in  $B_d$  mixing of approximately  $-7^\circ$ . This is shown in the lower left plot of Fig. 1. The predicted value for  $\sin 2\beta$  is now shifted to  $\sin 2\beta \approx 0.85$  [2, 7]. This value is significantly larger than the measured  $S_{\psi K_S}$  which allows to fit the experimental value of  $\epsilon_K$ . Note that this solution is characterized by a large value of  $R_b \simeq 0.47$ , that is significantly larger than its exclusive determinations but still compatible with the inclusive determinations. The angles  $\gamma \simeq 66^\circ$  and  $\alpha \simeq 87^\circ$  agree with the usual UT analysis.

3.  $\epsilon_K$  and  $S_{\psi K_S}$  are NP free while the determination of  $R_t$  through  $\Delta M_d/\Delta M_s$  is affected by NP. This is shown in the lower right plot of Fig. 1. In that scenario one finds  $\Delta M_d^{\text{SM}}/\Delta M_s^{\text{SM}}$  to be much higher than the actual measurement. In order to agree exactly with the experimental central value,

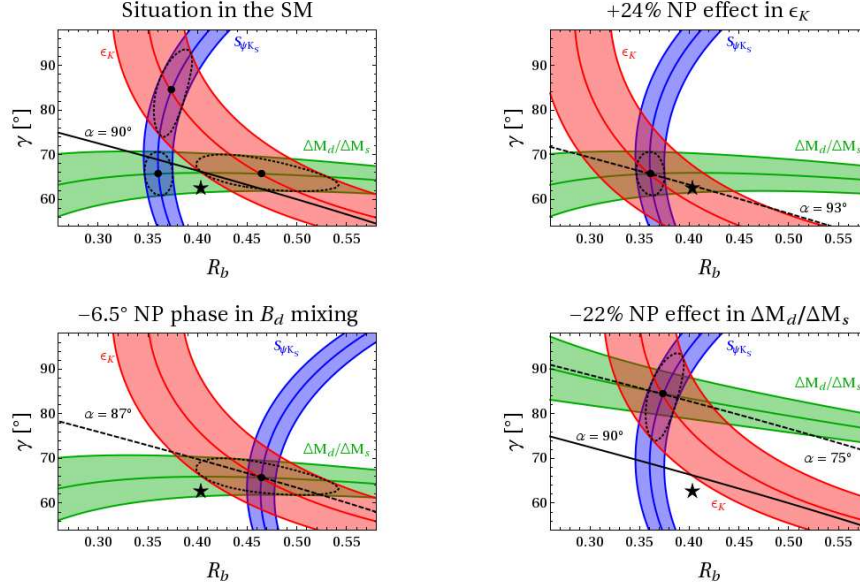


Fig. 1. The  $R_b - \gamma$  plane as discussed in the text. For further explanations see [3]

one needs a NP contribution to  $\Delta M_d/\Delta M_s$  at the level of  $-22\%$  leading to an increased value of  $R_t$  that compensates the negative effect of NP in  $\Delta M_d/\Delta M_s$ . This in turn allows to fit the experimental value of  $\epsilon_K$ . This solution is characterized by a large value of  $\gamma \simeq 84^\circ$  and  $\alpha$  much below  $90^\circ$ . The latter fact could become problematic for this solution when the determination of  $\alpha$  further improves.

4. The value of  $|V_{cb}|$  is significantly increased to roughly  $43.5 \cdot 10^{-3}$ , which seems rather unlikely.

The first three NP scenarios characterized by black points in Fig. 1 will be clearly distinguished from each other once the values of  $\gamma$  and  $R_b$  from tree level decays will be precisely known. Moreover, if future measurements of  $(R_b, \gamma)$  will select a point in the  $R_b - \gamma$  plane that differs from the black points in Fig. 1, it is likely that NP will simultaneously enter  $\epsilon_K$ ,  $S_{\psi K_S}$  and  $\Delta M_d/\Delta M_s$ . It will be interesting to monitor future progress in the  $R_b - \gamma$  plane.

### 3.3. Correlations in Supersymmetric Flavour Models

The correlations between various observables in the LHT model [8] and in the RS model with custodial protection [9,10] have been already discussed at this workshop by Recksiegel and Duling, respectively. Therefore I will confine my discussion to supersymmetric flavour models (SF) with flavour

symmetries that allow a simultaneous understanding of the flavour structures in the Yukawa couplings and in SUSY soft-breaking terms, adequately suppressing FCNC and CP-violating phenomena and solving SUSY flavour and CP problems. A recent detailed study of various SF models has been performed in [3] and I will summarize the results of this work here.

We have analysed the following representative scenarios in which NP contributions are characterized by:

- i) The dominance of right-handed (RH) currents (abelian model by Agashe and Carone),
- ii) Comparable left- and right-handed currents with CKM-like mixing angles represented by the special version (RVV2) of the non-abelian  $SU(3)$  model by Ross, Velasco and Vives as discussed recently by Calibbi et al and the model by Antusch, King and Malinsky (AKM),
- iii) The dominance of left-handed (LH) currents in non-abelian models ( $\delta LL$ ) .

We find [3]:

**1.** The ratio  $Br(B_d \rightarrow \mu^+ \mu^-)/Br(B_s \rightarrow \mu^+ \mu^-)$  in the AC and RVV2 models is dominantly below its CMFV prediction and can be much smaller than the latter. In the AKM model this ratio stays much closer to the MFV value of roughly  $1/33$  and can be smaller or larger than this value with equal probability. Still, values of  $Br(B_d \rightarrow \mu^+ \mu^-)$  as high as  $1 \times 10^{-9}$  are possible in all these models as  $Br(B_s \rightarrow \mu^+ \mu^-)$  can be strongly enhanced. We show this in the case of the RVV2 model in the left plot of Fig. 2.

**2.** Interestingly, in the  $\delta LL$ -models, the ratio  $Br(B_d \rightarrow \mu^+ \mu^-)/Br(B_s \rightarrow \mu^+ \mu^-)$  can not only deviate significantly from its CMFV value, but in contrast to the models with right-handed currents considered by us can also be larger than the MFV value. Consequently,  $Br(B_d \rightarrow \mu^+ \mu^-)$  as high as  $(1-2) \times 10^{-9}$  is possible while being consistent with the bounds on all other observables, in particular the one on  $Br(B_s \rightarrow \mu^+ \mu^-)$ . We show this in the right plot of Fig. 2.

**3.** The  $S_{\psi\phi}$  anomaly within the supersymmetric flavour models with right-handed currents implies, in the case of the AC and AKM models, values of  $Br(B_s \rightarrow \mu^+ \mu^-)$  as high as several  $10^{-8}$ . This are very exciting news for the CDF, D0 and LHCb experiments! In the RVV2 model such values are also possible but not necessarily implied by the large value of  $S_{\psi\phi}$ . We show one example of this spectacular correlation for the case of the AC model in the left plot of Fig. 3.

**4.** In the AC model a large value of  $S_{\psi\phi}$  implies a solution to the  $(g-2)_\mu$  anomaly as seen in the right plot of Fig. 3. In the RVV2 and the AKM models additionally  $Br(\mu \rightarrow e\gamma)$  in the reach of the MEG experiment

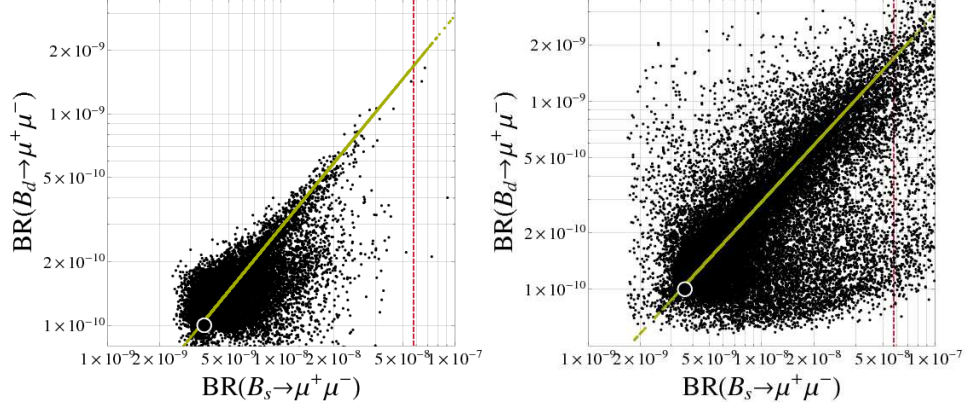


Fig. 2.  $B_{d,s} \rightarrow \mu^+\mu^-$  branching ratios in the RVV2 model (left) and the  $\delta$ LL model (right) as obtained in [3].

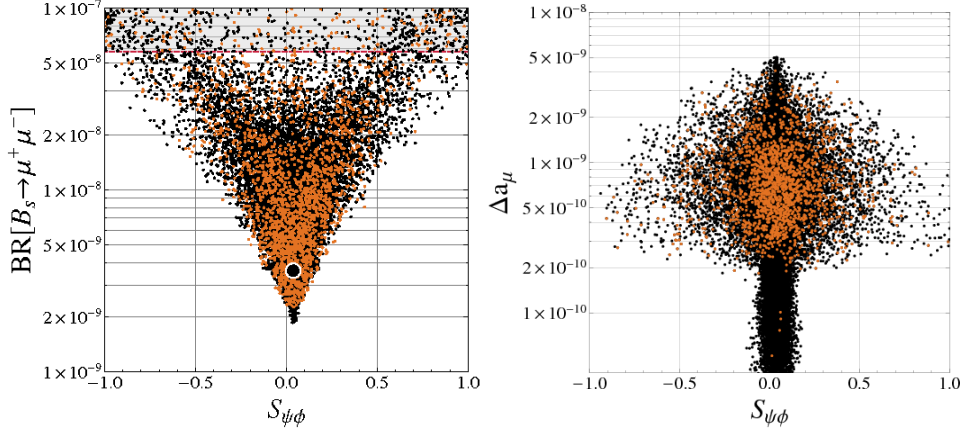


Fig. 3.  $Br(B_s \rightarrow \mu^+\mu^-)$  vs.  $S_{\psi\phi}$  (left) and  $\Delta a_\mu$  vs.  $S_{\psi\phi}$  (right) in the AC model as obtained in [3].  $a_\mu = (g-2)_\mu/2$ .

is implied. In the case of the RVV2 model,  $d_e \geq 10^{-29}$  e cm. is predicted, while in the AKM model it is typically smaller. Moreover, in the case of the RVV2 model,  $Br(\tau \rightarrow \mu\gamma) \geq 10^{-9}$  is then in the reach of Super-B machines, while this is not the case in the AKM model. Some of these results are illustrated in Fig. 4.

**5.** In the supersymmetric models with exclusively left-handed currents ( $\delta$ LL), the desire to explain the  $S_{\phi K_S}$  anomaly implies automatically a solution to the  $(g-2)_\mu$  anomaly and the direct CP asymmetry in  $b \rightarrow s\gamma$  much

larger than its SM value. We illustrate this in Fig. 5. This is in contrast to the models with right-handed currents where the  $A_{\text{CP}}^{bs\gamma}$  remains SM-like.

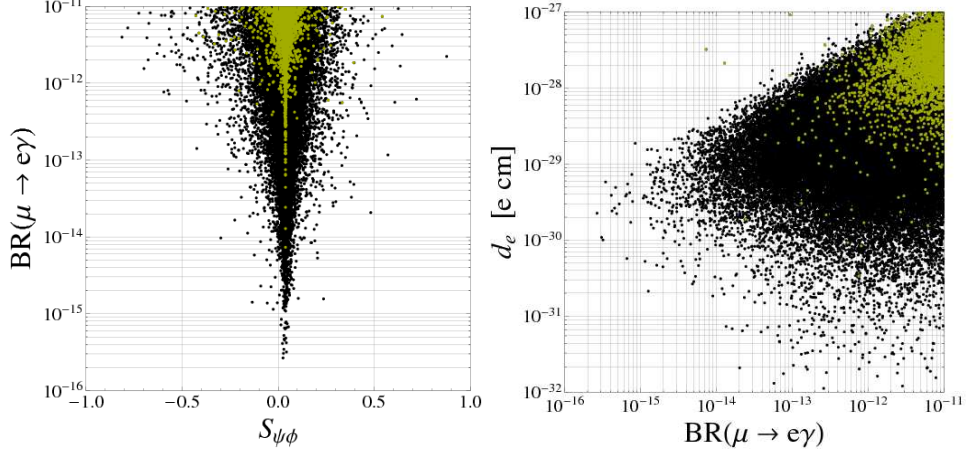


Fig. 4.  $Br(\mu \rightarrow e\gamma)$  vs.  $S_{\psi\phi}$  (left) and  $d_e$  vs.  $Br(\mu \rightarrow e\gamma)$  (right) in the RVV2 model as obtained in [3]. The green points explain the  $(g-2)_\mu$  anomaly at 95% C.L., i.e.  $\Delta a_\mu \geq 1 \times 10^{-9}$ .

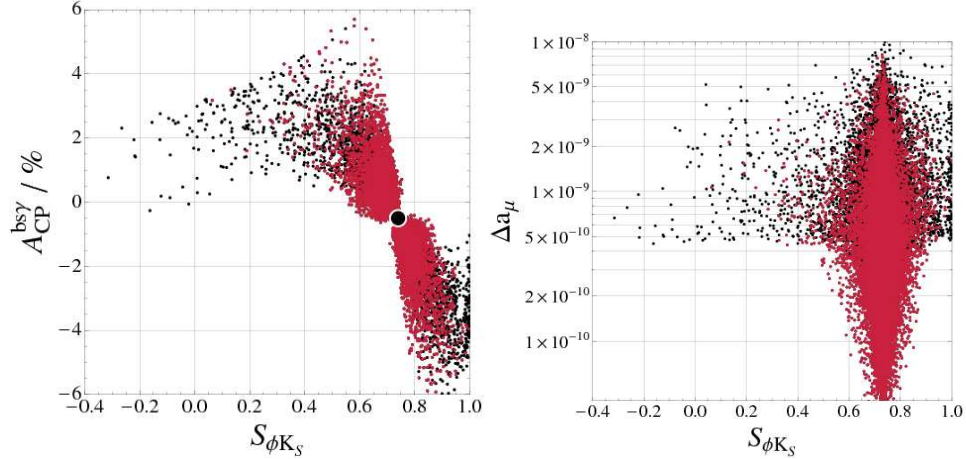


Fig. 5.  $A_{\text{CP}}^{bs\gamma}$  vs.  $S_{\phi K_S}$  (left) and  $\Delta a_\mu$  vs.  $S_{\phi K_S}$  (right) in the  $\delta\text{LL}$  model as obtained in [3]. The red points satisfy  $Br(B_s \rightarrow \mu^+\mu^-) \leq 6 \times 10^{-9}$ .



### 3.4. Maximal Enhancements in Various Models

Finally, we present in Table 1 approximate maximal enhancements for  $Br(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ ,  $Br(K_L \rightarrow \pi^0 \nu \bar{\nu})$ ,  $Br(B_s \rightarrow \mu^+ \mu^-)$  and  $S_{\psi\phi}$  in various models. Brief description of all these models can be found in [1].

Model	$Br(K^+ \rightarrow \pi^+ \nu \bar{\nu})$	$Br(K_L \rightarrow \pi^0 \nu \bar{\nu})$	$Br(B_s \rightarrow \mu^+ \mu^-)$	$S_{\psi\phi}$
CMFV	20%	20%	20%	0.04
MFV	30%	30%	1000%	0.04
AC	2%	2%	1000%	1.0
RVV2	10%	10%	1000%	0.50
AKM	10%	10%	1000%	0.30
$\delta$ LL	2%	2%	1000%	0.04
LHT	150%	200%	30%	0.30
RSc	60%	150%	10%	0.75

Table 1. Approximate maximal enhancements for various observables in different models of NP. In the case of  $S_{\psi\phi}$  we give the maximal positive values. The NP models have been defined in [3].

## 4. Final Messages and Five Big Questions

In our search for a more fundamental theory we need to improve our understanding of flavour physics. The study of flavour physics in conjunction with direct collider searches for new physics, with electroweak precision tests and cosmological investigations will result one day in a NSM. When this will happen is not clear at present. Afterall, 35 years have passed since the completion of the present SM and no fully convincing candidate for the NSM exists in the literature. On the other hand in view of presently running and upcoming experiments, the next decade could be like 1970's in which practically every year a new important discovery has been made. Even if by 2019 a NSM may not exist yet, it is conceivable that we will be able to answer the following crucial questions by then:

- Are there any fundamental scalars with masses  $M_s \leq 1 \text{ TeV}$ ?
- Are there any new fundamental fermions like vector-like fermions or the 4th generation of quarks and leptons?
- Are there any new gauge bosons leading to new forces at very short distance scales and an extended gauge group?
- What are the precise patterns of interactions between the gauge bosons, fermions and scalars with respect to flavour and CP Violation?



- Can the answers to these four questions help us in understanding the BAU and other fundamental cosmological questions?

There are of course many other profound questions in elementary particle physics and cosmology but from my point of view I would really be happy if in 2019 satisfactory answers to the five questions posed above were available.

In this presentation I wanted to emphasize that many observables in the quark and lepton flavour sectors have not been measured yet or only poorly measured and that flavour physics only now enters the precision era. Indeed, spectacular deviations from the SM and MFV expectations are still possible in flavour physics. The interplay of the expected deviations with direct searches at Tevatron, LHC and later at ILC will be most interesting. Finally, the correlations between various observables will pave the road to the NSM.

#### Acknowledgements

I would like to thank the organizers for inviting me to this very pleasant and interesting workshop. I would also like to thank all my collaborators for a wonderful time we spent together exploring different avenues beyond the Standard Model. This research was supported by the Deutsche Forschungsgemeinschaft (DFG) under contract BU 706/2-1, the DFG Cluster of Excellence ‘Origin and Structure of the Universe’ and by the German Bundesministerium für Bildung und Forschung under contract 05HT6WOA.

#### REFERENCES

- [1] A. J. Buras, hep-ph/0910.1032.
- [2] A. J. Buras and D. Guadagnoli, Phys. Rev. D **78** (2008) 033005, hep-ph/0805.3887.
- [3] W. Altmannshofer, A. J. Buras, S. Gori, P. Paradisi and D. M. Straub, hep-ph/0909.1333.
- [4] M. Bona *et al.* [UTfit Collaboration], hep-ph/0908.3470.
- [5] A. J. Buras, F. Parodi and A. Stocchi, JHEP **0301** (2003) 029, hep-ph/0207101.
- [6] W. Altmannshofer, A. J. Buras and D. Guadagnoli, JHEP **0711** (2007) 065, hep-ph/0703200.
- [7] E. Lunghi and A. Soni, Phys. Lett. B **666** (2008) 162, hep-ph/0803.4340.
- [8] M. Blanke, A. J. Buras, B. Duling, S. Recksiegel and C. Tarantino, hep-ph/0906.5454.
- [9] M. Blanke, A. J. Buras, B. Duling, S. Gori and A. Weiler, JHEP **0903** (2009) 001, hep-ph/0809.1073.
- [10] M. Blanke, A. J. Buras, B. Duling, K. Gemmler and S. Gori, JHEP **0903** (2009) 108, hep-ph/0812.3803.